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## THE ORIGIN AND EVOLUTION OF LIFE UPON THE EARTH<sup>52</sup>

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### LECTURE I, PART II

#### PRIMORDIAL ENVIRONMENT—ENERGY DERIVED FROM THE SUN'S HEAT AND LIGHT—LIFE ELEMENTS IN THE SOLAR SPECTRUM

IN the change from the lifeless to the living world the *properties* of the "life elements" become known as *functions*.

The earliest function of living matter appears to have been to capture and transform the electric energy of those chemical elements which throughout we designate as the "life elements." This function appears to have developed only in the presence of heat energy, derived either from the earth or from the sun. This is the first example in the life process of the utilization of energy wherever it may be found. At a later stage of evolution life captured the light energy of the sun through the agency of chlorophyll, the green coloring matter of plants.

If the lifeless surface of the primordial earth was like that of the moon—covered not only with igneous rocks but with piles of heat-storing débris, as recently described by Russell<sup>53</sup>—the reflecting power of the earth's surface represented a loss of 40 per cent. of the sun's heat, as compared with the present reflecting power of the earth which results in a loss of 47 per cent. of the sun's heat; while the solar radiation constant, as measured by Abbott, is 1.923.

The primal dependence of the electric energy of life on the original heat energy of the earth or on solar heat is demonstrated by the universal behavior of the most primitive organisms, because when the temperature of protoplasm is lowered 0° C. the velocity of the chemical reactions becomes so small that in most cases all manifestations of life are suspended, that is, life becomes latent. Some bacteria grow at or very near the freezing point of water (0° C.) and possibly primordial bacteria-like organisms grew below that point. Even now the common "hay bacillus" grows at 6° C.<sup>54</sup> Rising temperatures increase the velocity of the biochemical reactions of protoplasm up to an optimum temperature, beyond which they are increasingly injurious and finally fatal to all organisms. In hot springs some of the Cyanophyceæ (blue-green algæ), primitive plants intermediate in evolution between bacteria

<sup>52</sup> Fourth course of lectures on the William Ellery Hale Foundation, National Academy of Sciences, delivered at the meeting of the academy at Washington, on April 17 and 19, 1916.

<sup>53</sup> Russell, H. N., 1916, p. 75.

<sup>54</sup> Jordan, Edwin O., 1908, pp. 67, 68.

and algæ, sustain temperatures as high as 63° C. and, as a rule, are killed by a temperature of 73° C., which is probably the coagulation point of their proteins. Setchell found bacteria living in water of hot springs at 89° C.<sup>55</sup> In the next higher order of the Chlorophyceæ (green algæ) the temperature fatal to life is lower, being 43° C.<sup>56</sup> Very much higher temperatures are endured by the spores of certain bacilli which survive until temperatures of from 105° C. to 120° C. are reached. There appears to be no known limit to the amount of dry cold which they can withstand.<sup>57</sup>

It is this power of the relatively water-free spores to resist heat and cold which has suggested to Richter (1865), to Kelvin, and to Arrhenius (1908) that living germs may have pervaded space and may have reached our planet either in company with meteorites (Kelvin)<sup>58</sup> or driven by the pressure of light (Arrhenius).<sup>59</sup> The fact that so far as we know life has only originated once and not repeatedly appears to dispose of these hypotheses; nor is it courageous to put off the problem of life origin into cosmic space instead of resolutely seeking it within the forces and elements of our own humble planet.

The thermal conditions of living matter point to the probability that life originated when portions at least of the earth's surface and waters had temperatures of between 89° C. and 6° C.; and also to the possibility of the origin of life before the atmospheric vapors admitted a regular supply of sunlight.

After the sun's heat living matter appears to have captured the sun's light which is essential, directly or indirectly, to all living energy higher than that of the most primitive bacteria. The discovery by Lavoisier (1743-1794) and the development (1804) by de Saussure<sup>60</sup> of the theory of photosynthesis, namely, that sunshine, combining solar heat and light, is a perpetual source of living energy, laid the foundations of biochemistry and opened the way for the establishment of the law of the conservation of energy within the living organism. This was the first conception of the cycle of the elements continually passing through plants and animals which was so grandly formulated by Cuvier in 1817.<sup>61</sup>

<sup>55</sup> *Op. cit.*, p. 68.

<sup>56</sup> Loeb, Jacques, 1906, p. 106.

<sup>57</sup> Cultures of bacteria have even been exposed to the temperature of liquid hydrogen (about -250° C.) without destroying their vitality or sensibly impairing their biologic qualities. This temperature is far below that at which any chemical reaction is known to take place, and is only about 23 degrees above the absolute zero point at which, it is believed, molecular movement ceases. On the other hand, when bacteria are frozen in water during the formation of natural ice the death rate is high. See Jordan, Edwin O., 1908, p. 69.

<sup>58</sup> Poulton, Edward B., 1896, p. 818.

<sup>59</sup> Pirsson, Louis V., and Schuchert, Charles, 1915, pp. 535, 536.

<sup>60</sup> De Saussure, N. T., 1804.

<sup>61</sup> Cuvier, Baron Georges L. C. F. D., 1817, p. 13.

La vie est donc un tourbillon plus ou moins rapide, plus ou moins compliqué, dont la direction est constante, et qui entraîne toujours des molécules de mêmes sortes, mais où les molécules individuelles entrent et d'où elles sortent continuellement, de manière que la *forme* du corps vivant lui est plus essentielle que sa *matière*.

#### CHEMICAL COMPOSITION OF CHLOROPHYLL

Carbon .....	73.34
Hydrogen .....	9.72
Nitrogen .....	5.68
Oxygen .....	9.54
Phosphorus .....	1.38
Magnesium .....	0.34
	<hr/> 100.00

The green coloring matter of plants is known as chlorophyll; its chemical composition according to Hoppe-Seyler's analysis is given here.<sup>62</sup> Potassium is essential for its assimilating activity. Iron (often accompanied by manganese) although essential to the production of chlorophyll is not contained in it. The chlorophyll-bearing leaves of the plant in the presence of sunlight separate the oxygen atoms from the carbon and hydrogen atoms in the molecules of carbon dioxide ( $\text{CO}_2$ ) and of water ( $\text{H}_2\text{O}$ ), storing up the energy of the hydrogen and carbon in the carbohydrate substances of the plant, an energy which is

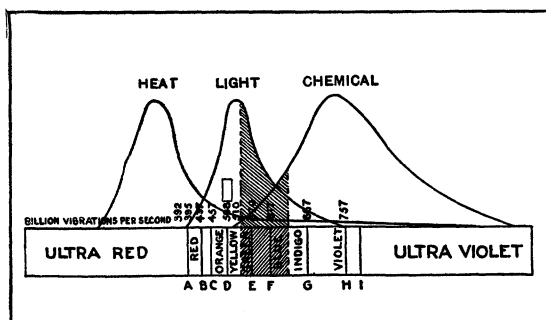


FIG. 1. CURVES SHOWING THE OVERLAPPING OF THE HEAT, LIGHT, AND CHEMICAL WAVES OF THE SUN. After Dahlgren.

stored by deoxidation and which can be released only through reoxidation. Thus the celluloses, sugars, starches, and other similar substances which deposit their kinetic energy in the tissues of the plant, release that energy through the addition of oxygen, the amount of oxygen required being the same as that needed to burn similar substances in the air to the same degree; in brief, a combustion which generates heat.<sup>63</sup> Thus living matter utilizes the energy of the sun to draw a continuous stream of electric energy from the elements in the earth, the water, and the atmosphere.

This was the first step in the interpretation of life processes in the

<sup>62</sup> Sachs, Julius, 1882, p. 758.

<sup>63</sup> W. J. Gies.

terms of physics and chemistry. What was regarded 100 years ago as a special vital force in the life of plants proved to be an adaptation of physico-chemical forces. The chemical action of chlorophyll is not fully understood, but it is known to absorb most vigorously the solar rays between B and C of the spectrum,<sup>64</sup> and these rays are most effective in assimilation. While the effect of the solar rays between D and E is minimal those beyond F are again effective. In heliotropic movements both of plants and animals the blue rays are more effective than the red.<sup>65</sup> Spores given off as ciliated cells from the algæ seek first the blue rays. Since the food supply of animals is primarily derived from chlorophyll-bearing plants animals are less directly dependent on the solar light and solar heat while the chemical life of plants fluctuates throughout the day with the variations of light and temperature. Thus Richards<sup>66</sup> finds in the cacti that the breaking down of the acids through the splitting of the acid compounds is a respiratory process caused by the alternate oxidation and deoxidation of the tissues through the action of the sun.

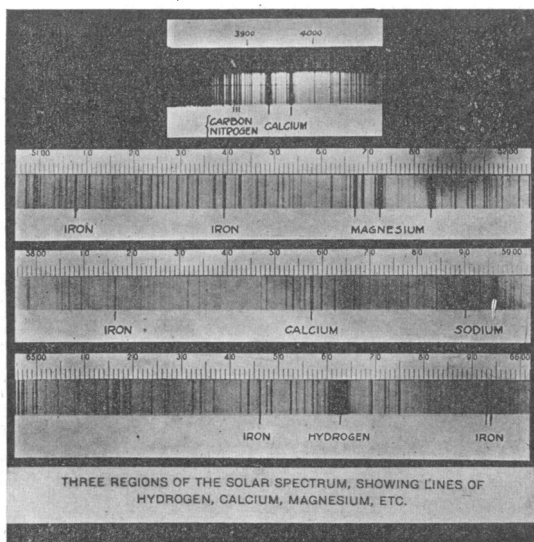


FIG. 2. THREE REGIONS OF THE SOLAR SPECTRUM SHOWING THE LINES OF CARBON, NITROGEN, CALCIUM, IRON, MAGNESIUM, SODIUM AND HYDROGEN. From the Mt. Wilson Observatory.

The solar energy transformed into the chemical potential energy of the compounds of carbon, hydrogen, and oxygen in the plants is transmuted by the animal into motion and heat and then dissipated. Thus in the life cycle we observe both the conservation and the degradation of

<sup>64</sup> Loeb, Jacques, 1906, p. 115.

<sup>65</sup> *Op. cit.*, p. 127.

<sup>66</sup> Richards, Herbert M., 1915, pp. 34, 73-75.

energy, corresponding with first and second laws of thermodynamics developed in physics by the researches of Newton, Helmholtz, Phillips, Kelvin, and others.<sup>67</sup>

#### "LIFE ELEMENTS" IN THE SUN AND IN OUR PLANET

We have thus observed that the primal earth, air and water contained all the chemical elements and three of the most simple but important chemical compounds, namely, water, nitrates and carbon dioxide, which are known to be essential to the pre-chlorophyllic and chlorophyllic stages of the life process. An initial step in the origin of life was the coordination or bringing together of these elements which, so far as we know, had never been in combined action before and are widely distributed as they appear in the solar spectrum. Therefore, before examining the properties of these elements further, it is interesting to trace them back into the sun and thus into the cosmos.

Excepting hydrogen and oxygen, the principal elements which enter into the formation of protoplasm are minor constituents of the mass of matter sown throughout space in comparison with the rock-forming elements.<sup>68</sup> Again excepting hydrogen, their lines in the solar spectrum are for the most part weak and only shown on high dispersion plates, while hydrogen is represented by very strong lines as shown by spectroheliograms of solar prominences. The lines of oxygen are relatively faint; it appears principally as a compound, titanium oxide ( $\text{TiO}_2$ ), in sunspots although a triple line in the extreme red seems also to be due to it. In the chromosphere, or higher atmosphere of the sun, hydrogen is not in a state of combustion, and the fine hydrogen prominences show radiations comparable to those in a vacuum tube.<sup>69</sup>

Nitrogen, the next most important life element, is displayed in the so-called cyanogen bands of the ultra-violet, made visible by high dispersion photographs. Carbon is shown in many lines in green, which are relatively bright near the sun's edge; it is also present in comets, and carbonaceous meteorites (Orgueil, Kold Bokkeveld, etc.) are well known. Graphite occurs in meteoric irons.

In the solar spectrum so far as studied no lines of the "life elements," phosphorus, sulphur, and chlorine, have been detected. On the other hand, the metallic elements which enter into the life compounds, iron, sodium and calcium, are all represented by strong lines in the solar spectrum, the exception being potassium in which the lines are faint. Of the eight metallic elements which are most abundant in the earth's crust as well as the non-metallic elements carbon and silicon, six are also among the eight strongest in the solar spectrum. In general, however, the important life elements are very widely distributed

<sup>67</sup> Henderson, Lawrence J., 1913, pp. 15-18.

<sup>68</sup> Russell, Henry Norris, letter of March 6, 1916.

<sup>69</sup> Hale, George Ellery, letter of March 10, 1916.

in the stellar universe, showing most prominently in the hotter stars, and in the case of hydrogen being universal.

#### ACTION AND REACTION AS ADAPTIVE PROPERTIES OF THE LIFE ELEMENTS

Of the total of eighty-two or more chemical elements thus far discovered at least twenty-nine are known to occur in living organisms either invariably, frequently, or rarely, as shown in the accompanying Table II of the Life Elements. The adaptation of the life elements is due to their incessant action and reaction, each element having its peculiar and distinctive forms of action and reaction, which in the organism are transmuted into functions. Such activity of the life elements is largely connected with forms of electric energy which the physicists call *ionization*, while the correlated or coordinated *interaction* of various groups of life elements is largely connected with processes which the chemists term *catalysis*. Of catalysis we shall speak later.

*Ionization*, the actions and reactions of all the elements and electrolytic compounds—according to the hypothesis of Arrhenius, first put forth in 1887—is primarily due to electrolytic dissociation whereby the molecules of all acids (*e. g.*, carbonic acid,  $\text{H}_2\text{CO}_3$ ), bases (*e. g.*, sodium hydroxide,  $\text{NaOH}$ ), and salts (*e. g.*, sodium chloride,  $\text{NaCl}$ ) give off streams of the electrically charged particles known as ions. Ionization is dependent on the law of Nernst that the greater the dielectric capacity of the solvent (*e. g.*, water) the more rapid will be the dissociation of the substances dissolved in it, other conditions remaining the same. Thus ions are atoms or groups of atoms carrying electric charges which are positive when given off from metallic elements, and negative when given off from non-metallic elements. Electrolytic molecules, according to this theory, are constantly dissociating to form ions and the ions are as constantly recombining to form molecules. Since the salts of the various mineral elements are constantly being decomposed through electrolytic ionization, they play an important part in all the life phenomena; and since similar decomposition is induced by currents of electricity, indications are that all the development of living energy is in a sense electric.

In Rutherford's experiments on radioactive matter<sup>70</sup> he tells us that in the phosphorescence caused by the approach of an emanation of radium to zinc sulphate the atoms throw off the alpha particles to the number of five billion each second with velocities of 10,000 miles a second; that the alpha particles in their passage through air or other medium produce from the neutral molecules a large number of negatively charged ions, and that this ionization is readily measurable.

Phosphorescence in plants and animals is also regarded by Loeb<sup>71</sup> as

<sup>70</sup> Rutherford, Sir Ernest, 1915, p. 115.

<sup>71</sup> Loeb, Jacques, 1906, pp. 66-68.

a form of radiant energy. While developed in a number of living animals—including the typical glowworms in which the phenomenon was first investigated by Faraday—the living condition is not essential to it because the phosphorescence continues after death and may be produced in animals by non-living material. Many organisms show phosphorescence at comparatively low temperatures, yet the presence of free oxygen appears to be necessary.

Finally, we observe that ionization is connected with the radioactive elements, of which thus far only radium has been detected in the organic compounds although the others may be present.

The ionizing electric properties of the life elements are a matter of first importance. We observe at once in the table below that all the great structural elements which make up the bulk of plant and animal tissues are of the non-metallic group with negative ions, with the single exception of hydrogen which has positive ions. All these elements are of low atomic weight and several of them develop a great amount of heat in combustion, hydrogen and carbon leading in this function of the

TABLE II

THE LIFE ELEMENTS, SHOWING THEIR PRINCIPAL PROPERTIES AND FUNCTIONS IN PLANTS AND ANIMALS

Mainly or Wholly with or in Negative Ions <sup>72</sup>		Mainly or Wholly with or in Positive Ions <sup>72</sup>		
Non-metallic		Metallic		
<sup>73</sup> Carbon ( <i>e. g.</i> , <sup>75</sup> carbonates)	Silicon	<sup>77</sup> Hydrogen	<sup>78</sup> Iron	Lithium
<sup>73</sup> Oxygen ( <i>e. g.</i> , <sup>75</sup> sulphates)	Iodine	Potassium	Copper	Nickel
<sup>73</sup> <sup>74</sup> Nitrogen ( <i>e. g.</i> , <sup>75</sup> nitrates)	Bromine	Sodium	Aluminum	Radium
<sup>73</sup> Phosphorus ( <i>e. g.</i> , <sup>75</sup> phosphates)	Fluorine	Calcium	Barium	Strontium
<sup>73</sup> Sulphur ( <i>e. g.</i> , <sup>75</sup> sulphates)	Boron	Magnesium	Cobalt	Zinc
Chlorine	<sup>75</sup> Arsenic	Manganese	Lead	

*Ionization Elements thus far Discovered in Living Organisms*

<sup>72</sup> An ion is an atom or group of atoms carrying an electric charge. The positive ions (cations) of the metallic elements move toward the cathode: the negative ions (anions) given off by the non-metallic elements move toward the anode.

<sup>73</sup> Together with hydrogen conspicuous in living colloids and non-electrolytes—very little in the indicated ionized forms.

<sup>74</sup> Occurs also, as  $\text{NH}_4$ , in *positive* ions. Here the hydrogen overbalances the nitrogen.

<sup>75</sup> Substances occurring in living matter.

<sup>76</sup> Arsenic itself is a metal, but in living compounds it is an analogue of phosphorus and occurs in *negative* ions when ionized.

<sup>77</sup> Pictet has obtained results indicating that liquid and solid hydrogen are metallic. Hydrogen is metallic in *behavior*, though non-metallic in *appearance*.

<sup>78</sup> Iron in living compounds is chiefly non-ionized, colloidal. Apparently this is also true of copper, aluminum, barium, cobalt, lead, nickel, strontium and zinc. As to radium, however, there is no information on this point.

*Elements Invariably Present in Living Organisms<sup>79</sup>*

Atomic Weight	Heat Combustion per Gram	Element	Symbol	Plants	Animals
1.008	34.702 cal. (H <sub>2</sub> )	<i>Hydrogen</i>	H	Hydrogen, carbon, oxygen, and nitrogen—"C, O, H, N"—are <i>essential and of chief rank</i> in all life processes; forming, with sulphur, practically all plant and animal proteins, and, with phosphorus, forming the nucleoproteins.  In nucleoproteins and phospholipins.	In nucleoproteins and phospholipins; in some brachiopods; in blood; and in vertebrate bone and teeth.
12.005	8.08 "	<i>Carbon</i>	C		
16.00	0.143 "	<i>Oxygen</i>	O		
14.01	14.01 "	<i>Nitrogen</i>	N		
31.04	5.747 "	<i>Phosphorus</i>	P	In most proteins, 0.1-5.0 per cent. Abundant in marine plants, esp. "kelps" (larger <i>Phaeophyceae</i> ); activity of chlorophyll depends on it.  Present in large quantities in <i>Corallinaceae</i> (a family of calcified red algae).  Present in large quantities in certain algae (chiefly marine).  Essential in the formation of protoplasm.	In most proteins, 0.1-5.0 per cent. In blood, muscle, etc.
32.06	2.22 "	<i>Sulphur</i>	S		
39.16	1.745 "	<i>Potassium</i>	K		
24.32	6.077 "	<i>Magnesium</i>	Mg		
40.07	3.284 "	<i>Calcium</i>	Ca	Believed essential to all plants, but not demonstrated; found in marine plants, esp. <i>Phaeophyceae</i> . Present in many plants; believed by some to be essential; abundant in marine algae, esp. in the <i>Phaeophyceae</i> .  Found in all plants; present in large quantities in the <i>Diatomaceae</i> , both fresh-water and marine; in form of "silica" constitutes 0.5-7.0 per cent. of the ash of ordinary marine algae.	Present in echinoderms and alcyonarians; <sup>80</sup> present in all parts of vertebrates, esp. in bones. In all parts of vertebrates; abundant in bones and teeth Essential in the formation of protoplasm, and in the higher animals; essential in hemoglobin as an oxygen carrier. Present in all animals; abundant in blood and lymph. Present in all animals; abundant in blood and lymph; present in the gastric juice.  Present in radiolarians and siliceous sponges; also in all the higher animals.
55.84	1.353 "	<i>Iron</i>	Fe		
23.00	3.293 "	? <i>Sodium</i>	Na		
35.46	0.254 "	? <i>Chlorine</i>	Cl		
28.3		? <i>Silicon</i>	Si		

<sup>79</sup> Observe that the most active elements in organic compounds generally have low atomic weights; and that the most active element, hydrogen, has the highest combustion heat in calories per gram.

<sup>80</sup> Magnesium is also found in many other invertebrates than those mentioned.

*Elements Frequently Present in Living Organisms*

Atomic Weight	Heat Combustion per Gram	Element	Symbol	Plants	Animals
126.92	0.1766 cal.	<i>Iodine</i>	I	In marine plants, esp. the "brown algæ," <i>Phaeophyceæ</i> ; in <i>Laminaria</i> and <i>Fucus</i> ; also in some Gorgonias.	Essential in the higher animals (thyroid).
54.93 79.92		<i>Manganese</i> <i>Bromine</i>	Mn Br	In some plants. In marine plants, esp. the "brown algæ," <i>Phaeophyceæ</i> ; in some Gorgonias.	In most animals in very slight proportions. In some animals in very slight proportions.
19.0		<i>Fluorine</i>	F	In a few plants.	In some animals—constituent of bones and teeth; in shells of molluscs and in vertebrate bones.

*Elements Rarely Present in Living Organisms*

Atomic Weight	Heat Combustion per Gram	Element	Symbol	Plants	Animals
27.1 74.96 137.37 11.0 58.97 63.57	1.463 cal. 0.952 "	<sup>81</sup> <i>Aluminium</i> <sup>81</sup> <i>Arsenic</i> <sup>81</sup> <i>Barium</i> <i>Boron</i> <sup>81</sup> <i>Cobalt</i> <sup>81</sup> <i>Copper</i>	Al As Ba B Co Cu	In a few plants. In a few plants. In some plants. In a few plants. In a few plants.	In a few animals. In some animals.
207.20 6.94 58.08 226.0 87.63 65.37	0.243 " 1.497 " 1.291 "	<sup>81</sup> <i>Lead</i> <i>Lithium</i> <sup>81</sup> <i>Nickel</i> <i>Radium</i> <sup>81</sup> <i>Strontium</i> <sup>81</sup> <i>Zinc</i> †	Pb Li Ni Ra Sr Zn	In some plants. In a few plants. In some plants. In a few plants. In a few plants.	Traces in some corals; essential in some lower animals as oxygen carrier. Traces in some corals. In some animals. In a few animals; traces in some corals.

The exceedingly rare occurrence of cerium, chromium, didymium, lanthanum, molybdenum, silver and vanadium is in all probability merely adventitious.

<sup>81</sup> Commonly regarded as poisons when present in *mineral* (ionic) forms, even in small proportions.

release of energy, which invariably takes place in the presence of oxygen. On the other hand, the lesser components of organic compounds are the metallic elements with positive ions, such as potassium, sodium, calcium, and magnesium, calcium combining with carbon or with phosphorus as the great structural or skeletal builder in animals. There is also so much carbonaceous protein in the animal skeleton that in animals calcium takes the place of carbon in plants only in the sense that it reduces the *proportion* of carbon in the skeleton: it shares the honors with carbon.

In general the electric action and reaction of the non-metallic and the metallic elements dissolved or suspended in water is believed to be the source of all the internal functions of life, which are developed always in the presence of oxygen and with the energy either of the heat of the earth, or of the sun, or of both the heat and light of the sun.

#### COSMIC PROPERTIES AND LIFE FUNCTIONS OF THE CHIEF LIFE ELEMENTS

Both the time and the mode of the origin of life is a matter of pure speculation, in which we have as yet no observation or uniformitarian reasoning to guide us, for all the experiments of Bütschli and others to imitate the original life process have proved fruitless. We may, however, put forward four hypotheses in regard to it, as follows:

First: we may advance the hypothesis that an early step in the organization of living matter was the assemblage one by one of several of the ten elements essential to life, namely, hydrogen, oxygen, nitrogen, phosphorus, sulphur, potassium, calcium, magnesium, iron (also perhaps silicon), and carbon, which are present in all living organisms with the exception of some of the most primitive forms of bacteria, which may lack carbon, magnesium, iron and silica. Of these the four most important elements were obtained from their previous combination in water ( $H_2O$ ), from the nitrogen compounds of volcanic emanations or from the atmosphere,<sup>82</sup> consisting largely of nitrogen and from atmospheric carbon dioxide ( $CO_2$ ). The remaining six elements, phosphorus, sulphur, potassium, calcium, magnesium and iron, came from the earth.

Second: whether there was a sudden or a more or less serial grouping of these elements, one by one, we are led to a second hypothesis that they were gradually bound by a new form of mutual attraction whereby the actions and reactions of a group of life elements established a new form of unity in the cosmos, an organic unity or *organism* quite distinct from the larger and smaller aggregations of inorganic matter previously held or brought together by the forces of gravity. Some such stage of

<sup>82</sup> Ammonia is also formed by electrical action in the atmosphere and unites with the nitric oxides to form ammonium nitrate or nitrite: these compounds fall to earth in rain.—F. W. Clarke.

mutual attraction may have been ancestral to the cell, the primordial unity and individuality of which we shall describe later.

Third: this leads to the hypothesis that this grouping occurred in the gelatinous state described as "colloidal" by Graham.<sup>83</sup> Since all living cells are colloidal it appears probable that this grouping of the "life elements" took place in a state of colloidal suspension, for it is in this state that the life elements best display their incessant action, reaction and interaction. Bechhold<sup>84</sup> observes that

Whatever the arrangement of matter in living organisms in other worlds may be, it must be of colloidal nature. What other condition except the colloidal could develop such changeable and plastic forms, and yet be able, if necessary, to preserve these forms unaltered?

Fourth: with this assemblage, mutual attraction, and colloidal condition, a fourth hypothesis is that there arose the rudiments of competition and selection. Was there any stage in this grouping, assemblage, and organization of life forms, however remote or rudimentary, when the law of natural selection did not operate between different unit aggregations of matter? Probably not, because *each of the chemical life elements possesses its peculiar properties which in living compounds best serve certain functions.* This cooperation was also an application of energy new to the cosmos. In other words, every element, as shown

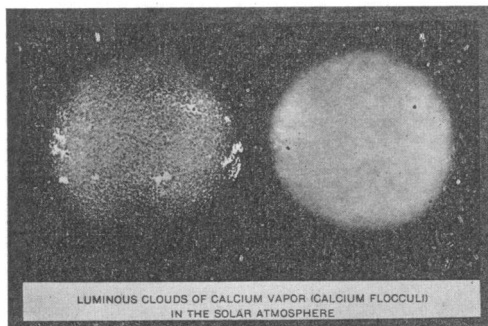


FIG. 3. TWO PHOTOGRAPHS OF THE SUN SHOWING (LEFT) THE CLOUDS OF CALCIUM VAPOR IN THE SOLAR ATMOSPHERE, AND (RIGHT) GROUPS OF SUN SPOTS. From the Mt. Wilson Observatory.

in Table II., "The Life Elements" (pp. 176-178), and in the descriptions below, has its single or multiple services to render to the organism.

*Hydrogen*, the life element of least atomic weight, is always near the surface of the typical hot stars. Rutherford<sup>85</sup> tells us that while the hydrogen atom is the lightest known its negatively charged electrons

<sup>83</sup> Over fifty years ago Thomas Graham introduced the term "colloid" (*L. colla*, glue) to denote coagulating substances like gelatine, a typical colloid, as distinguished from crystalloids. Proteins belong to that class of colloids which, once coagulated, can not return to the liquid condition.

<sup>84</sup> Bechhold, Heinrich, 1912, p. 194.

<sup>85</sup> Rutherford, Sir Ernest, 1915, p. 113.

are only about 1/1800 of the mass of the hydrogen atom: they are liberated from metals on which ultra-violet light falls, and can be released from atoms of matter by a variety of agencies. Hydrogen is present in all acids and in most organic compounds. It also has the highest power of combustion.<sup>86</sup> Its ions are very important factors in animal respiration and in gastric digestion.<sup>87</sup> It is very active in dissociating or separating oxygen from various compounds, and through its affinity for oxygen forms water ( $H_2O$ ), the principal constituent of protoplasm.

*Oxygen*, like hydrogen, has an attractive power which brings into the organism other elements useful in its various functions. It makes up two thirds of all animal tissue as it makes up one half of the earth's crust. Beside these attractive and synthetic functions its great service is as an oxidizer in the release of energy; it is thus always circulating in the tissues. Through this it is involved in all heat production and in all mechanical work, and affects cell division and growth.<sup>88</sup>

*Nitrogen* comes next in importance to hydrogen and oxygen as structural material<sup>89</sup> and when combined with carbon and sulphur gives the plant and animal world one of the chief organic food constituents, protein. It was present on the primordial earth, not only in the atmosphere but also in the gases and waters emitted by volcanoes. Combined with hydrogen it forms various radicles of a basic character (*e. g.*,  $NH_2$  in amino acids,  $NH_4$  in ammonium compounds); combined with oxygen it yields acidic radicles such as  $NO_3$  in nitrates. It combines with carbon in  $C \equiv N$  radicles and in  $\equiv C - NH_2$  and  $=C = NH$  forms, the latter being particularly important in protoplasmic chemistry.<sup>90</sup> This life element forms the basis of all explosives, it also confers the necessary instability upon the molecules of protoplasm because it is loath to combine with and easy to dissociate from most other elements. Thus we find nitrogen playing an important part in the physiology of the most primitive organisms known, the nitrifying bacteria.

*Carbon* also exists at or near the surface of cooling stars which are becoming red.<sup>91</sup> It unites vigorously with oxygen, tearing it away from neighboring elements, while its tendency to unite with hydrogen is less marked. At lower heats the carbon compounds are remarkably stable, but they are by no means able to resist great heats; thus Barrell<sup>92</sup> observes that a chemist would immediately put his finger on the element carbon as that which is needed to endow organic substance with complexity of form and function, and its selection in the origin of plant life

<sup>86</sup> Henderson, Lawrence J., 1913, pp. 218, 239, 245.

<sup>87</sup> Gies, W. J.

<sup>88</sup> Loeb, Jacques, 1906, p. 16.

<sup>89</sup> Henderson, Lawrence J., 1913, p. 241.

<sup>90</sup> Gies, W. J.

<sup>91</sup> Henderson, Lawrence J., 1913, p. 55.

<sup>92</sup> Barrell, Joseph, letter of March 20, 1916.

was by no means fortuitous. Including the artificial products the known carbon compounds exceed 100,000, while there are thousands of compounds of C, H, and O, and hundreds of C and H.<sup>93</sup> Carbon is so dominant in living matter that biochemistry is very largely the chemistry of carbon compounds; and it is interesting to observe that in the evolution of life each of these biological compounds must have arisen suddenly as a saltation or mutation, there being no continuity between one chemical compound and another.

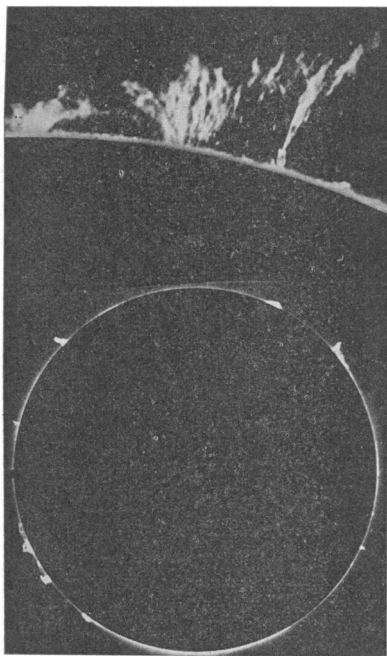


FIG. 4. (LOWER) SOLAR PROMINENCES SURROUNDING THE SUN. (UPPER) THE SAME GREATLY ENLARGED. From Mt. Wilson Observatory.

*Phosphorus* is essential in the nucleus of the cell,<sup>94</sup> being a large constituent of the intranuclear germ plasm, or chromatin, which is the seat of heredity. It enters largely into the structure of nerves and brain, and also, as phosphates of calcium and magnesium, serves an entirely diverse function as building material for the skeletons of animals.

*Sulphur*, uniting with nitrogen, oxygen, hydrogen and carbon, is an essential constituent of the proteins of plants and animals.<sup>95</sup> It is especially conspicuous in the epidermal protein known as keratin, which by its insolubility mechanically protects the underlying tissues.<sup>96</sup> Sulphur

<sup>93</sup> Henderson, Lawrence J., 1913, p. 193.

<sup>94</sup> *Op. cit.*, p. 241.

<sup>95</sup> *Op. cit.*, p. 242.

<sup>96</sup> Pirsson, Louis V., and Schuchert, Charles, 1915, p. 434.

is also contained in one of the physiologically important substances of bile.<sup>97</sup>

*Potassium* separates hydrogen from its union with oxygen in water, and is the most active of the metals, biologically considered, in its positive ionization.<sup>98</sup> Through stimulation and inhibition potassium salts play an important part in the regulation of life phenomena, and they are essential to the living tissues of plants and animals, fresh-water and

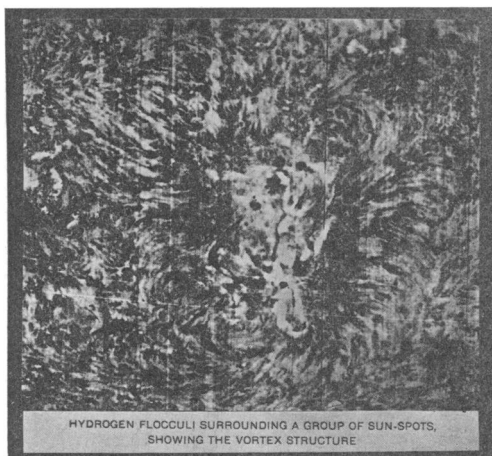


FIG. 5. HYDROGEN FLOCCULI SURROUNDING A GROUP OF SUN SPOTS SHOWING THE VORTEX STRUCTURE. From the Mt. Wilson Observatory.

marine plants, in particular, storing up large quantities in their tissues.<sup>99</sup> Potassium is of service to life in building up complex compounds from which the potassium can not be dissociated as a free ion; it is thus one of the building stones of living matter.<sup>100</sup>

*Magnesium* is fourth in order of activity among the metallic elements. It is essential to the chlorophyll, or green coloring matter of plants, which in the presence of sunshine serves in the dissociation of oxygen from the carbon of carbon dioxide and the hydrogen of water. It is also found in the skeletons of many invertebrates and in the coral-line algæ.

*Calcium* is third in order of activity among the metallic elements. According to Loeb<sup>101</sup> it plays an important part in the life phenomena through stimulation (irritability) and inhibition. It unites with carbon as carbonate of lime and is contained in many of those animal skeletons which, through deposition, make up an important part of the earth's crust. In invertebrates the carbonate, except in certain brachiopods, is

<sup>97</sup> Gies, W. J.

<sup>98</sup> Caesium is more electropositive.—F. W. Clarke.

<sup>99</sup> Loeb, Jacques, 1906, p. 94.

<sup>100</sup> *Op. cit.*, p. 72.

<sup>101</sup> *Op. cit.*, 1906, p. 94.

far more important as skeletal material than the phosphates: the limestones form only about five per cent. of the sedimentaries. Shales and sandstones are far more abundant.

*Iron* is essential for the production of chlorophyll<sup>102</sup> though, unlike magnesium, it is not contained in it. It is present as well in all protoplasm, while in the higher animals it serves, in the form of oxy-hemoglobin, as a carrier of oxygen from the lungs to the tissues.<sup>103</sup>

*Sodium* is less important in the nutrition of plant tissues, but serves an essential function in all animal life in relation to movement through muscular contraction.<sup>104</sup> Its salts, like those of calcium, play an important part in the regulation of life phenomena through stimulation and inhibition.<sup>105</sup>

*Iodine*, with its negative ionization, becomes useful through its capacity to unite with hydrogen in the functioning of the brown algæ and in many other marine organisms. It is also an organic constituent in the thyroid gland of the vertebrates.<sup>106</sup> The iodine content of crinoids—stalked echinoderms—varies widely in organisms gathered from different parts of the ocean according to the temperature and the iodine content of the sea-water. Iodine and bromine are important constituents of the organic axes of gorgonias.

*Chlorine*, like iodine, a non-metallic element with negative ions, is abundant in marine algæ and present in many other plants, while in animals it is present in both blood and lymph. In union with hydrogen as hydrochloric acid it serves a very important function in the gastric digestion of proteins.<sup>107</sup>

*Barium*, rarely present in plants, has been used in animal experimentation by Loeb, who has shown that its salts induce muscular peristalsis and accelerate the secretory action of the kidneys.<sup>108</sup>

*Copper* ranks first in electric conductivity. In the invertebrates, in the form of hemocyanine, it acts as an oxygen carrier in the fluid circulation to the tissues.<sup>109</sup> It is always present in certain molluscs, such as the oyster, and also in the plumage of a bird, the Turaco. Although among the rare life elements it ranks first in toxic action upon fungi, algæ, and in general upon all plants, yet it is occasionally found in the tissues of trees growing in copper-ore regions.<sup>110</sup>

In general most of the metallic compounds and several of the non-metallic compounds are toxic or destructive to life when present in large

<sup>102</sup> Sachs, Julius, 1882, p. 699.

<sup>103</sup> Henderson, Lawrence J., 1913, p. 241.

<sup>104</sup> Loeb, Jacques, 1906, p. 79.

<sup>105</sup> *Op. cit.*, pp. 94, 95.

<sup>106</sup> Henderson, Lawrence J., 1913, p. 242.

<sup>107</sup> *Op. cit.*, p. 242.

<sup>108</sup> Loeb, Jacques, 1906, p. 93.

<sup>109</sup> Henderson, Lawrence J., 1913, p. 241.

<sup>110</sup> Howe, M. A., letter of February 24, 1916.

quantities. All the mineral elements of high atomic weight are toxic in comparatively minute proportions, while the essential life elements of low atomic weight are toxic only in comparatively large proportions. Toxicity depends largely upon the liberation of ions, and non-ionized and non-ionizable organic compounds—such as hemoglobin containing non-ionizable iron—are wholly non-toxic.

We thus return to the conception set forth above in our four hypotheses that in the origin and early evolution of the life-organism the gradual selection and grouping of the ten chief life elements and of the nineteen or more subsequently added may have been analogous to a series of inventions and discoveries or to the successive addition of new characters and functions such as we may trace through paleontology in the origin and development of the higher plants and animals.

Prior to the entrance into the organism of the active metals there may have arisen the utilization of the binary compounds of carbon and oxygen ( $\text{CO}_2$ ) and of hydrogen and oxygen ( $\text{H}_2\text{O}$ ), to the attractive power of which Henderson<sup>111</sup> has especially drawn our attention. He points out that it is the attraction of oxygen or of hydrogen or of both combined which is now bringing and in the past may have brought into the organism other elements useful to it in its various functions. In other words, oxygen and hydrogen were *selective* agents. In fact, those inorganic compounds which contain neither hydrogen, carbon, nor oxygen make up but a very small percentage of the substance of known bodies. Further, the most active inorganic compounds contain either hydrogen or oxygen. All acids contain hydrogen, most of them oxygen as well, and many bases contain oxygen, although such bases as ammonium ( $\text{NH}_4$ ) do not. Thus hydrogen and oxygen are elements unrivaled in chemical activity, which enable living organisms to make use of other elements at need.

The incorporation of the active metals, potassium, sodium, calcium, magnesium, iron, manganese and copper, into the substance of living organisms may have occurred in the order of their activity in capturing energy from the environment and storing it within the organism. For example, an immense period of time may have been traversed before there occurred the addition of magnesium and iron to certain hydrocarbons which enabled the plant to draw upon the energy of solar light.

#### ADAPTATION IN THE COLLOIDAL STATE

In the lifeless world matter occurred both in the crystalloidal and colloidal states. It is in the latter state, as observed above (p. 180), that life originated. It is a state peculiarly favorable to action, reaction, and interaction, or the free interchange of physico-chemical energies. Each organism is in a sense a container full of a watery solution in which

<sup>111</sup> Henderson, Lawrence J., 1913, pp. 239, 240.

various kinds of colloids are suspended.<sup>112</sup> Such a suspension involves a play of the energies of the free particles of matter in the most delicate equilibrium, and the suspended particles exhibit the vibrating movement attributed to the impact of the molecules.<sup>113</sup> These free particles are of greater magnitude than the individual molecules, in fact, they represent molecules and multimolecules; and all the known properties of the compounds known as "colloids" can be traced to feeble molecular affinities between the molecules themselves, causing them to unite and to separate in multimolecules. Among the existing living colloids are certain carbohydrates, like starch or glycogen, proteins (compounds of carbon, hydrogen, oxygen and nitrogen with sulphur or phosphorus), and the higher fats. The colloids of protoplasm are dependent for their stability on the constancy of acidity and alkalinity, which is more or less regulated by the presence of bicarbonates.<sup>114</sup>

Electrical charges in the colloids<sup>115</sup> are demonstrated by currents of electricity sent through a colloidal solution, and are interpreted by Freundlich as due to electrolytic dissociation of the colloidal particles, alkaline colloids being positively charged while acid colloids are negatively charged. The concentration of hydrogen and hydroxyl ions in the ocean and in the organism is automatically regulated by carbonic acid ( $\text{CO}_2$ ).<sup>116</sup>

Among the colloidal substances in living organisms the so-called enzymes are very important since they are responsible for many of the processes in the organism. Possibly enzymes are not typical colloids and perhaps, in pure form, they may not be classified as such; but if they are not colloids they certainly behave like colloids.<sup>117</sup>

#### COORDINATION OF THE PROPERTIES OF THE LIFE ELEMENTS THROUGH INTERACTION

We have thus far traced the actions and reactions of the life elements, which are mainly contemporaneous, direct, and immediate; they do not suffice to form an organism. As soon as the grouping of chemical elements reaches the stage of an organism interaction becomes essential, for the chemical activities of one region of the organism must be harmonized with those of all other regions; the principle of interaction may apply at a distance and the results may not be contemporaneous. This is actually inferred to be the case in single-celled organisms such as the *Amœba*.<sup>118</sup>

The interacting and coordinating form of lifeless energy which has

<sup>112</sup> Bechhold, Heinrich, 1912.

<sup>113</sup> Smith, Alexander, 1914, p. 305.

<sup>114</sup> Henderson, Lawrence J., 1913, pp. 157-160.

<sup>115</sup> Loeb, Jacques, 1906, pp. 34, 35.

<sup>116</sup> Henderson, Lawrence J., 1913, p. 257.

<sup>117</sup> Hedin, Sven G., 1914, pp. 164, 173.

<sup>118</sup> Calkins, Gary N., 1916, pp. 259, 260.

proved to be of the utmost importance in the life processes in that recognized in the early part of the nineteenth century and denoted by the term catalysis, first applied by Berzelius in 1835. A catalyzer is a substance which modifies the velocity of a distant chemical reaction without itself being used up by the reaction. Thus chemical reactions may be accelerated or retarded and yet the catalyzer loses none of its energy. In a few cases it has been definitely ascertained that the catalytic agent does itself experience a series of changes. The theory is that catalytic phenomena depend upon the alternate decomposition and recomposition, or the alternate attachment and detachment of the catalytic agent.

Discovered as a property in the inorganic world catalysis has proved to underlie the great series of functions in the organic world which may be comprised in the physical term *interaction*. The researches of Ehrlich and others fully justify Huxley's prediction of 1881 that through therapeutics it would become possible "to introduce into the economy a molecular mechanism which, like a cunningly contrived torpedo, shall find its way to some particular group of living elements and cause an explosion among them, leaving the rest untouched." In fact, the interacting agents known as "enzymes" are such living catalyzers<sup>119</sup> which accelerate or retard reactions in the body by forming intermediary unstable compounds which are rapidly decomposed, leaving the catalyzer (*i. e.*, enzyme) free to repeat the action. Thus a small quantity of an enzyme can decompose indefinite quantities of a compound. The activity of enzymes is rather in the nature of the "interaction" of Newton than of direct action and reaction, because the results are produced at a distance and the energy liberated may be entirely out of proportion to the internal energy of the catalyzer. The enzymes being themselves complex organic compounds act specifically because they do not affect alike the different organic compounds which they encounter in the fluid circulation.

Hence, as a fifth hypothesis relating to the origin of organisms, we may advance the idea that the evolution and specialization of various catalyzers (including enzymes or "unformed ferments") has proceeded step by step with the evolution of plant and animal functions. In the evolution from the single-celled to the many-celled forms of life and the multiplication of these cells into hundreds of millions, into billions, and into trillions, as in the larger plants and animals, biochemical coordination and correlation become increasingly essential. In fact, none of the discoveries we have hitherto described throws greater illumination on the life processes than this connected with the internal secretions and the by-products of metabolism in the circulation of the plant and animal fluids. It is known that, as Huxley prophesied, enzymes do reach particular groups of living elements and leave others untouched. For example, the enzyme developed in the yeast ferment produces a different

<sup>119</sup> Loeb, Jacques, 1906, pp. 26, 28.

result in each one of a series of closely related carbohydrates.<sup>120</sup> Driesch<sup>121</sup> has suggested that within the nucleus of the cell is a storehouse of these ferments which pass out into the protoplasm tissues and there set up specific activities; and recently it has been suggested that it is hormones which affect certain hereditary determiners in the chromatin or germ plasm itself.

In 1849 there was given the first experimental proof of action exercised upon an organism by a ductless gland.<sup>124</sup> Berthold transplanted the testicles of young cocks, which afterward developed the masculine voice, sexual desire, comb, and love of combat, thus anticipating Brown-Sequard, who committed himself to the view that a gland, ductless or not, elaborated substances essential to the growth and maintenance of the body. Continuing the investigation of the *chemical correlation of the activities of animal bodies*, Bayliss and Starling proposed the name "hormones" (*ὁρμῶν*, to awaken, stir up). Hormone-producing agents develop from certain *endocrine* organs or glands of internal secretion. The secretion of a gland may act indirectly: *e. g.*, the influence of the thyroid by way of the thymus upon the activities of the stomach.

The heredity theory proposed by Cunningham<sup>122</sup> was based upon the discovery that the connection between the germ cells and the secondary sexual organs, which was supposed to be of a nervous nature, is really chemical. Since hormones from the germ cells determine the development of many other bodily organs, it is possible that hormones due to various cellular activities in the body may act upon the determiners in the germ cells which correspond to the tissues from which these hormones are derived. Cunningham's hypothesis suggests a means by which bodily modifications due to environmental and developmental conditions could modify corresponding determiners in the germ cells.

Catalytic action originates in the by-products of single chemical combinations. For example, the carbon dioxide liberated in cell metabolism acts at a distance on other portions of the cell and of the organism. "In a sense, too," observes Abel, "as has been frequently pointed out, every cell of the body furnishes in the carbon dioxide which it eliminates a hormone or product of internal secretion, since under normal conditions the carbon dioxide of the blood is one of the chief regulators of the respiratory center, influencing this center by virtue of its acidic properties."<sup>123</sup> But in the course of evolution certain entire cells and finally groups of cells took on this function of coordinating and correlating the activity of the complex organism. Thus certain glands arose.

Among the catalysers are those which accelerate general growth through stimulating specific chemical activities and others which retard

<sup>120</sup> Moore, F. J., 1915, p. 170; and Loeb, Jacques, 1906, pp. 21, 22.

<sup>121</sup> Wilson, Edmund B., 1906, p. 427.

<sup>122</sup> Cunningham, J. T., 1908, pp. 372-428.

<sup>123</sup> Abel, John J., 1915, p. 168.

<sup>124</sup> Halsted, William Stewart, 1914, pp. 224, 225.

general growth. There are also catalysers which accelerate or retard the growth of certain organs or parts of the body. The enzyme theory has developed with extreme rapidity but is still, doubtless, in its infancy.

In the concluding section of this lecture we shall trace these physical and chemical principles into some of the simpler forms of life.<sup>126</sup>

(To be continued)

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<sup>126</sup> In addition to the acknowledgments made in the introduction, I especially desire to express my indebtedness to Henry Norris Russell, of Princeton University, to George Ellery Hale, of the Mount Wilson Observatory, to Joseph Barrell and Charles Schuchert, of Yale University, who have kindly cooperated through correspondence and otherwise.

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